Development of a Solid Oxide Fuel Cell System for the Solid State Energy Conservation Alliance (SECA)

Steven R. Shaffer
Delphi Corporation
P.O. Box 20366
Rochester, NY 14602
(585) 359-6615
(585) 359-6061 fax
steven.shaffer@delphi.com

Magda Rivera
DOE Project Officer
National Energy Technology Lab
3610 Collins Ferry Road
P.O. Box 880
Morgantown, WV 26507-0880
(304)-285-1359
Magda.rivera@netl.doe.gov

Objectives

- Develop modular solid oxide fuel cell (SOFC) systems for a range of fuels.
- Develop a fuel cell system with natural gas-fueled stationary power generation.
- Develop a diesel-fueled mobile application.
- Develop a gasoline-fueled APU for mass-market applications.

Key Milestones

- Define system requirements
- Design stacks
- Develop steam reformer for natural gas
- Provide system design analysis and steering support
- Fabricate system
- Test system

Approach

The Delphi-Battelle team views solid oxide fuel cell (SOFC) as a highly competitive power source for a variety of stationary and mobile applications, as a device with high potential efficiencies and low emissions. It offers a solution to power for distributed power grids, automotive and truck power generation, and military power applications. Pursuing the high-volume automotive market will provide the drive for stack and balance-of-plant designs that will meet SECA's goals and facilitate volume production of SOFC systems. The reformer is the only major component that must be tailored for the specific fuel. Therefore, our approach is to pursue the transportation auxiliary power units (operating on gasoline and diesel) while simultaneously developing configurations for stationary distributed power generation using natural gas. The broad program of the Delphi-Battelle team will address all these systems over the 10 year duration of the SECA project. Our proposal focuses on key issues and items that require "breakthrough" developments to achieve the SECA goals. In all cases, the Delphi-Battelle team targets for performance and cost will meet or exceed those defined as the minimum goals for the three phases of the SECA project.

Our staged approach is to develop modular solid oxide fuel cell (SOFC) systems for a range of fuels and applications, starting with natural gas-fueled stationary power generation, proceeding through diesel-fueled mobile applications, and culminating with gasoline-fueled APUs for mass-market automotive applications. These goals are consistent with our business plan for SOFC technology.

Our proposed project will include design and integration of modular SOFC systems and will address development of the subsystems requiring the most technical innovation—the SOFC stack and the reformers. Breakthrough developments in these items are essential to meet Delphi-Battelle and SECA goals. Private investment by the Delphi-Battelle team (in addition to the proposed SECA project and our team's cost-share) will be focused on developing all other required subsystems and components, including the air delivery system, fuel delivery system, energy and water recovery subsystems, sensors and controls, control algorithms and software, safety systems, thermal management and insulation, enclosure and packaging, exhaust system, electrical signal and power conditioning. The private funding also will be used to develop lean, high-volume manufacturing methods for all of the system components. Because these privately funded activities are crucial to the SOFC modular system development effort, they will be controlled and managed by our project manager for the SECA project to ensure their successful completion and integration and to minimize risk. Also, the System Design and Integration Task, a part of the SECA project, will be responsible for setting technical specifications and development schedules for the privately funded balance-of-plant components.

The mass-market automotive APU application promises the highest manufacturing volume and therefore the lowest system cost due to economies of scale. However, it also presents some of the toughest application requirements for SOFC technology, particularly with respect to size, weight, start-up time, thermal cycling, and mechanical robustness; thus we anticipate that many of the challenging automotive APU targets will be accomplished only toward the end of Phase III. Therefore, although our team will immediately begin development of the gasoline-fueled automotive APU, during Phase I we will also develop, demonstrate, and begin to market a system for stationary distributed power generation with a separate steam reformer for natural gas. During Phase II, we also will develop and demonstrate, an advanced natural gas-fueled system that incorporates methane reforming within the stack. During Phase II, we will develop, demonstrate, and market a system for military and heavy-duty truck applications, using a diesel reformer. During Phase III, the challenging technical and cost targets for the mass-market gasoline-fueled automotive APU will be achieved. We envision this ultimate automotive configuration as a SOFC APU, with hydrogen-rich anode exhaust gas injected into the ultra-lean burn internal combustion engine, thereby providing very high overall vehicle fuel economy with very low emissions. The resulting effective SOFC fuel efficiency is expected to be in excess of 40 percent for DC electric power.

Our Phase I approach will focus on developing a steam reformer for natural gas, a gasoline catalytic partial oxidation (CPO) reformer for gasoline, and a robust 5-kW (net) SOFC stack that is expected to have a 2-hour start-up time. Due to the relatively long start-up time, the gasoline system will not yet be ready for high-volume automotive applications; development of this system will continue through Phases II and III. Balance-of-plant components, developed on the privately funded effort, will be integrated with the steam reformer and the SOFC stack to complete a system that runs on piped-in water and natural gas and is targeted for stationary distributed power applications. At the conclusion of Phase I, this pipeline natural gas system will be demonstrated for 1,500 hours steady state, with 10 start-up/shut-down cycles. We expect this system to exceed the SECA minimum efficiency, durability, and maintenance requirements.

Based on our experience with the proof-of-concept APU, we know that the system design and integration, the SOFC stack, and the reformer require substantial further development to meet the Phase I goals, and these are the focus of the proposed SECA project.

Results

The subject effort includes development of the SOFC stack and reformers. Also included are system design and integration, fabrication of demonstration systems, testing of demonstration systems, and reporting of results. Development of other balance-of-plant components (e.g., the air delivery system, fuel delivery system, sensors and controls, control algorithms and software, safety systems, insulation, enclosure and packaging, exhaust system, electrical signal and power conditioning) will be privately funded by Delphi, and is considered outside the scope of this program. However, Delphi will report on the general status of the privately funded effort at the same time it is reporting on the SECA-funded effort.

The following accomplishments were achieved.

System Design and Integration: The requirements for the 5-kW auxiliary power plant (APU) have been generated with the automotive (mobile) application as the focus. Progress towards the automotive requirements will satisfy many of the stationary power plant requirements. The general requirements of the power plant include the overall target volumetric and gravimetric power densities, overall conversion efficiency as well as the typical service life and duty requirements. Additionally, the start-up time, or latency has been specified.

One of the most highly influential requirements in the pursuit of an automotive APU conceptual system design is the volumetric power density. 10 liters/kW was the target used for initial system work. For the conceptual system design, a fixed package envelope was adopted as a starting point. This fixed package envelope necessitated some initial concept system integration and the definition of additional conceptual design requirements. Of these, the most important requirement pertains to the definition of a high temperature module (Hot-Zone-Module, HZM) and low temperature module (Plant-Support-Module, PSM) organization in the APU.

To support the conceptual design activity and meet the system requirements, an APU system mechanization has been created. This mechanization features several innovations that improve potential system performance and system packaging.

Two initial concepts were generated, given system requirements, conceptual design requirements and system mechanization. The concepts investigated were classified as the "T" and the "Square," based upon the general shape of the Hot-Zone-Module within the enclosure boundaries.

Within the prevailing design concept, two main concepts for modular APU insulation have been investigated. Each has apparent advantages and disadvantages. Additionally, the requirement for insulation performance has been determined in consideration of design constraints.

Process air blower requirements have been generated for the 5-kW APU. While the requirements of the blower are atypical, and commercial choices are limited, two technologies that offer promise for the automotive APU have been identified and characterized.

For the SOFC APU, much effort has been focused on the integration of system models and controls. Towards this end, a plant model with integrated controls has been developed to jointly support system analysis and concurrent control strategy development. The system model has been used to run many simulations of the 5-kW APU, featuring both straight POx reformer operation and anode tail gas recycling. The plant model has allowed for the verification of fundamental assumptions about the response and control of the SOFC APU.

Working within the fixed package size has been an extremely challenging engineering task; however, one that has produced many innovations in both system mechanization and design concept. The integration of the subsystems into the APU product was undertaken in an engineering evaluation mock-up (Figure 1). While executed mainly as a packaging verification exercise, many functional parts were used. The subsystems, now in various stages of development, have been guided by the integrated product requirements. The emphasis on the end-product form factor has produced a workable concept with realizable performance in a much smaller size than would normally have been attempted.

SOFC Stack Development: Progress has been made in stack development. The key achievements are:

- A Generation 2 stack design with metal cassettes as the repeating unit has been developed.
- Steady state modeling of this design has been carried out to understand flow, thermal and electrochemical behavior.
- Transient modeling has been carried out to understand the stresses for fast start-up in these designs.
- Cathode development has progressed with 7x7cm cell stacks demonstrating high power densities. Further work is ongoing to understand the processes that contribute to stable high power density performance of the cell.
- Fabrication of large cells of 12cm x 12cm dimensions has been successful for implementing into cassette builds.
- Bonding using the existing glass ceramic seal G18 has been further improved by new coating processes.
- New glass ceramic seals with better thermal expansion coefficient matching has been tested for adhesion. Further development is ongoing.
- Alternate seals have been developed, such as a silver based braze, and are being evaluated. Initial results from rupture test is very encouraging
- Multiple 3-cell stacks (7cm x7cm cells) have been successfully fabricated and tested for performance validation.

- 3-cell stack (7cm x 7cm cells) has been tested for 1,000 hour of durability.
- Successful fabrication and testing of 1- to 6-cell stacks with full sized (12cm x 12cm) cells.

ReforWER Developments: A production minded reformer system continues to be developed that includes integrated reformer, combustor and reformer air pre-heat function (ReforWER). Testing has been conducted that supports the viability of a homogenous mix combustor to provide clean start-up heat to the reactor. Several reactor designs have been built and tested that have pointed out areas of design/process weaknesses in need of further development, including:

- Combustor mixing geometry and temperature feedback
- Reactor lead edge temperature control
- Reformer thermal mass reduction / isolation
- Rapid heat up of reformer pre-heat air
- Braze related prototype manufacturing techniques

Catalyst: Significant improvements to gasoline partial oxidation catalyst formulations resulted in alumina or zirconia based compositions having excellent performance and durability at high operating temperatures for at least 50 hours of testing. Performance and thermodynamic modeling considerations were employed to suggest the best operating regime for gasoline partial oxidation to be between 900 and 950 °C and about 13 to 44 in^2 of washcoated surface area per g/min of fuel to be processed, for planar reactor configurations.

Conclusions

System Design and Integration: Working within the fixed package size has been an extremely challenging engineering task; however, one that has produced many innovations in both system mechanization and design concept. The integration of the subsystems into the APU product was undertaken in an engineering evaluation mock-up. While executed mainly as a packaging verification exercise, many functional parts were used. The subsystems, now in various stages of development, have been guided by the integrated product requirements. The emphasis on the end-product form factor has produced a workable concept with realizable performance in a much smaller size than would normally have been attempted.

SOFC Stack Development: The Delphi-Battelle team has successfully developed the Generation 2 stack design. Modeling under steady state and transient conditions has provided us a good understanding of the performance characteristics of this design. Parts have been fabricated, and extensive testing has been carried out to evaluating sealing concepts and electrode contact concepts. Progress has also been made on improving cathode to generate high power density. Finally, short stacks with full sized cells have been fabricated and tested under different conditions to validate the design.

Reformer Developments: Catalyst and process conditions can be selected to give good performance, selectivity, and durability for gasoline partial oxidation. Additional work is required for optimization of catalyst compositions and the corresponding processes in which the catalysts are to be used.

Figure 1: *Non-Functional Generation 2 SOFC APU*

The multi-layer, co-fired pSOFC approach offers a number of key advantages over competing approaches:

- Co-firing of cells leads to intimate electrode contact, which results in low polarization losses.
- Co-firing of interconnects with cells results in low contact resistance (a major source of resistance for metal interconnect stacks).
- Co-firing repeat units (and stacks) results in hermetic seals between interconnects and cell edges.
- Use of a zirconia-based interconnect removes a major source of stack degradation (thermal expansion mismatch and corrosion processes) and makes the stack more tolerant of thermal cycles.
- Flexibility in the design and manufacture of gas flow channels within the interconnect, permits optimization of air and fuel gas flow through stacks.
- Established high-volume, low-cost production methods.

Summary

With the support of the Department of Energy, Cummins Power Generation, and McDermott Technology, Inc.-SOFCo are developing a planar solid oxide fuel cell power system that will meet defined targets for technical and commercial performance. As this technology is brought into the power generation market place already served by Cummins Power Generation, it will substantially displace reciprocating and turbine engine power generation in target markets with attendant national benefits in reduced energy usage and emissions.